ISRU for Sustained Human Exploration of the Moon & Synergies with Lunar Science (and Commerce)

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Potential Lunar Resources

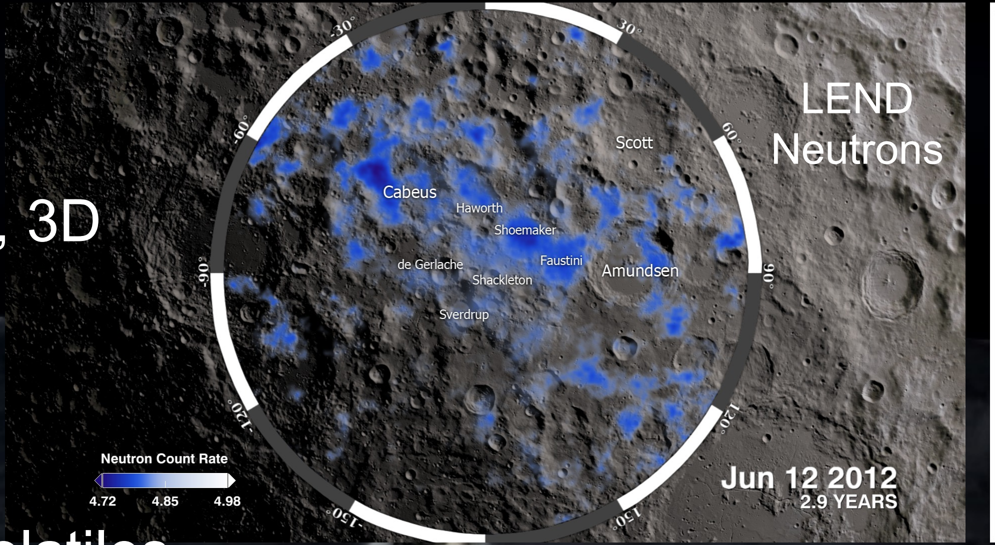
Polar volatile deposits

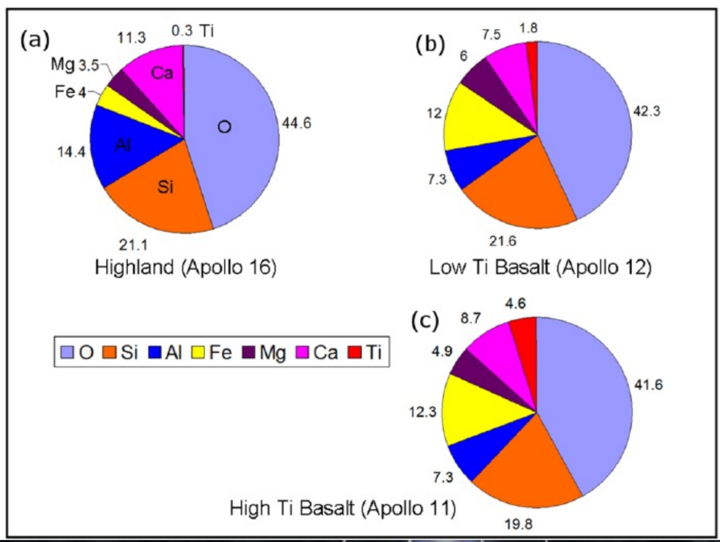
Regolith:

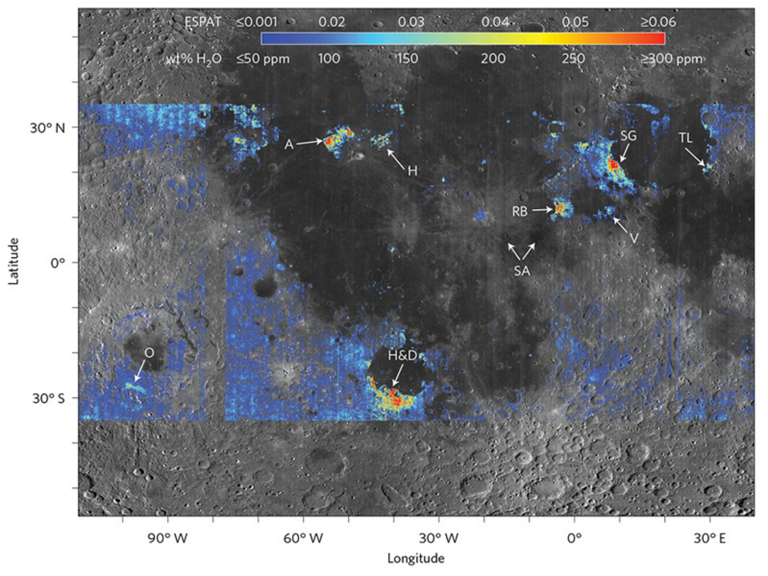
- Building materials (e.g., 3D printing),
- Metals,
- Oxygen
- Solar wind implanted volatiles (H, He C, N, etc.)
- Platinum group metals
- Rare earth elements
- Th, U

Pyroclastic Deposits

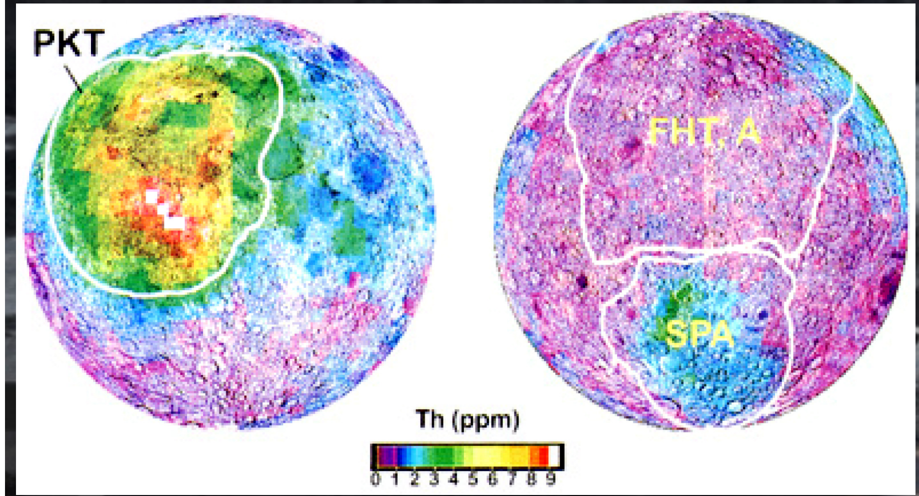
- Volatiles
- Metals







Milliken & Li (2017) *Nat. Geosci.* **10**, 561-565.



Jolliff et al. (2000) *JGR*. **105**, 4197-4216.

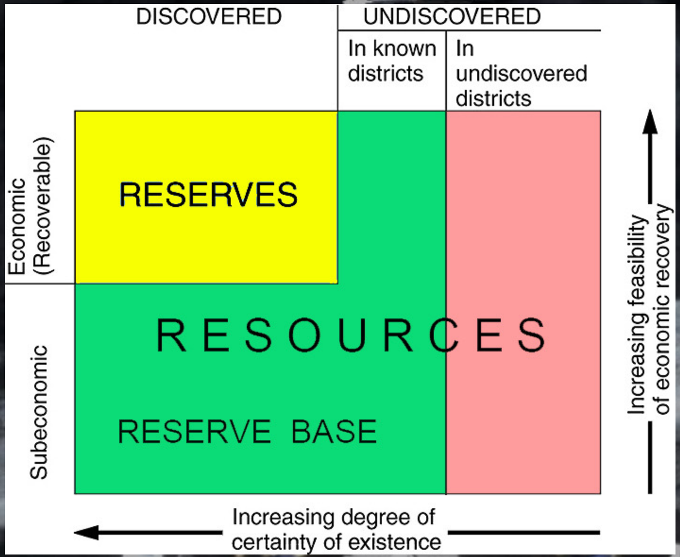
Lunar ISRU

- What measurements are needed to inform ISRU plans but are not presently in hand?
- What are the systems, interfaces, and organizational structures that exist or should be created to enable effective planning and execution of these measurements?

CONCLUSION 1: Critically needed: data to show that lunar resources are reserves.

CONCLUSION 2: An Artemis Program Office needs to be established.

RESOURCE: A concentration of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that *economic extraction of a commodity* is regarded as feasible, either currently or at some future time. Can be subdivided into Identified and Undiscovered (similar geological settings).



RESERVE: That portion of an identified resource from which a usable mineral or energy commodity can be *economically* and legally extracted at the time of determination. The term "ore" applies to reserves of some kinds of mineral commodities, generally metallic, but for want of another term it is sometimes applied to nonmetallic commodities.

Resources ≠ Reserves

From United States Geological Survey: https://pubs.usgs.gov/unnumbered/7000088/sta13.pdf

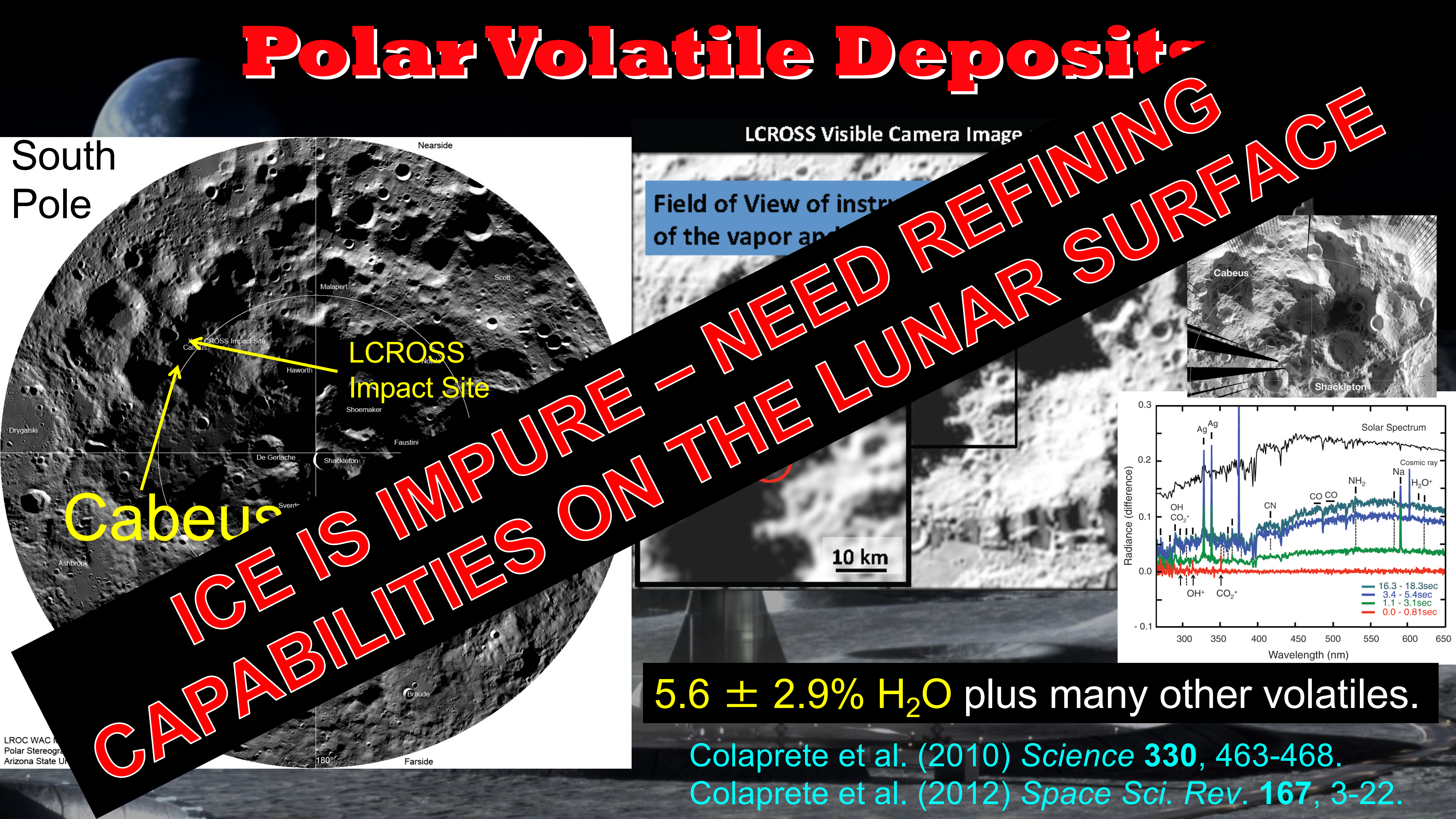
Understanding Lunar Resources

Need to know the following to know the reserve potential of lunar resources:

- 3D distribution;
- Form;
- Composition/concentration (grade);
- Regolith geotechnical properties;
- Ease of extractability and beneficiation.

A lunar resource prospecting *campaign* is needed, which will yield important data for science!

This could be international in nature, would not contravene the Outer Space Treaty, and potentially conducted through the Artemis Accords (see Neal, Abbud-Madrid, & Carpenter, 2021, LEAG Annual Meeting [https://www.hou.usra.edu/meetings/leag2021/pdf/5025.pdf])

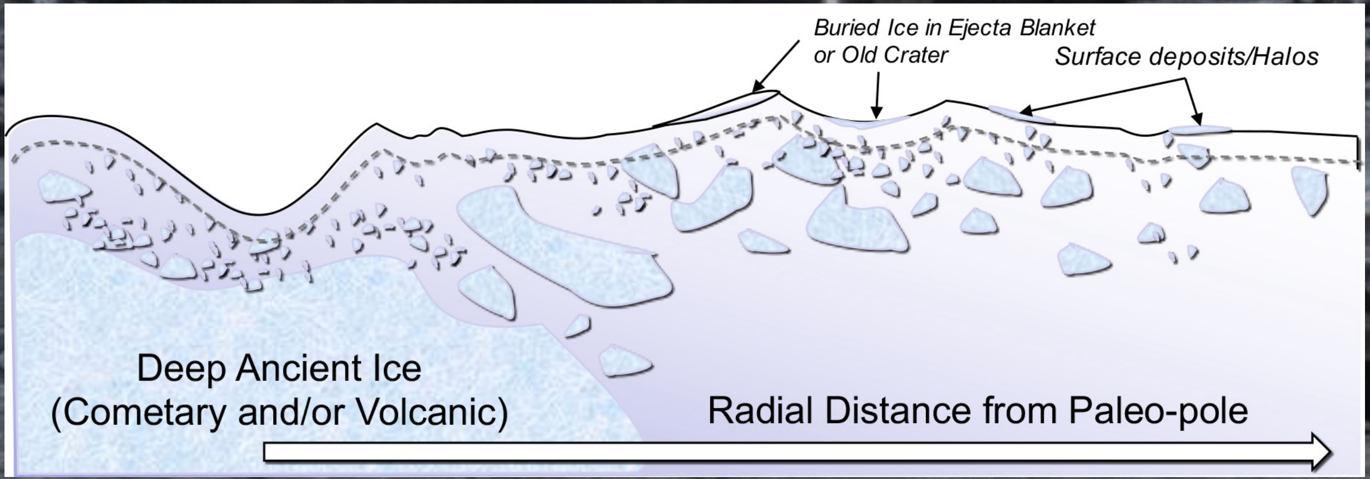


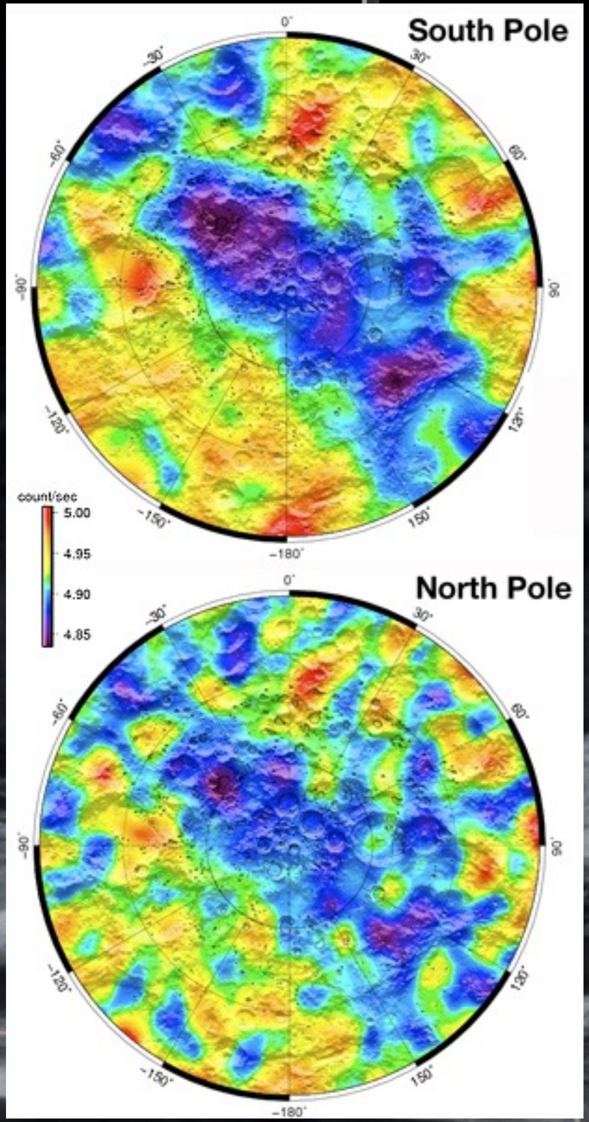
Polar Volatile Deposits
South Pole
Nearside
Scott
Malapert
LCROSS Impact Site
Haworth
LCROSS
Impact Site
Nobile
Shoemaker
Faustini
Drygalski
De Gerlache
Shackleton
Cabeus
Ashbrook
Braude
180°
Farside
LROC WAC
Polar Stereogra
Arizona State U
LCROSS Visible Camera Image
Field of View of instr
of the vapor an
10 km
Cabeus
Shackleton
Solar Spectrum
Cosmic ray
Radiance (difference)
Wavelength (nm)
16.3 - 18.3sec
3.4 - 5.4sec
1.1 - 3.1sec
0.0 - 0.81sec
ICE IS IMPURE – NEED REFINING
CAPABILITIES ON THE LUNAR SURFACE
5.6 ± 2.9% H_2O plus many other volatiles.
Colaprete et al. (2010) *Science* **330**, 463-468.
Colaprete et al. (2012) *Space Sci. Rev.* **167**, 3-22.

Polar Volatile Deposits

Science

- Understand the origin of such volatiles (endogenous vs. exogenous);
- Potentially understand the lunar volatile cycle;
- Investigate the delivery of volatiles to the inner Solar System;
- Explore if the building blocks for life are present in the deposits.

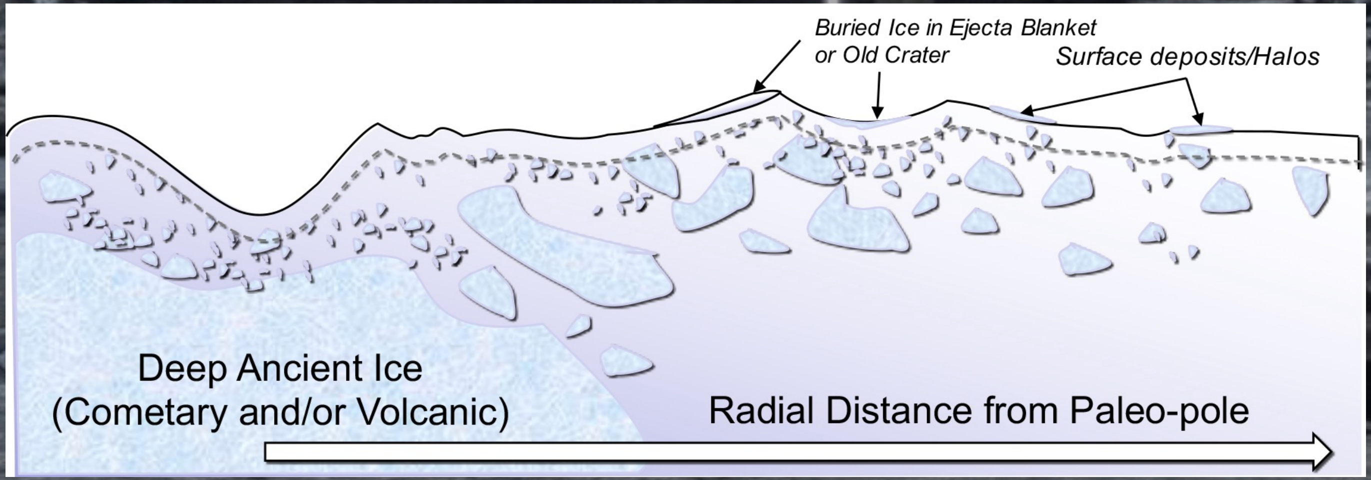


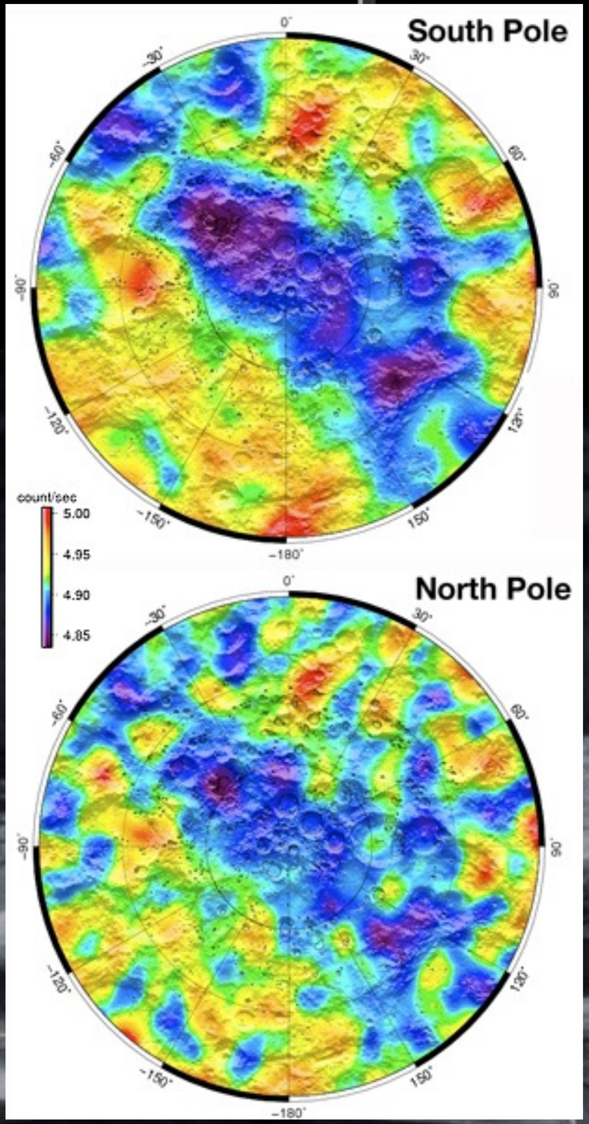


Polar Volatile Deposits

Exploration

- Define the distribution of such deposits within various PSRs - understand the form the volatiles are in;
- Explore the regolith geotechnical properties of regolith at extremely low temperatures;
- Understand volatile extractability from the regolith;
- Quantify the refining process for and transport and storage of potential life support consumables and rocket fuels.

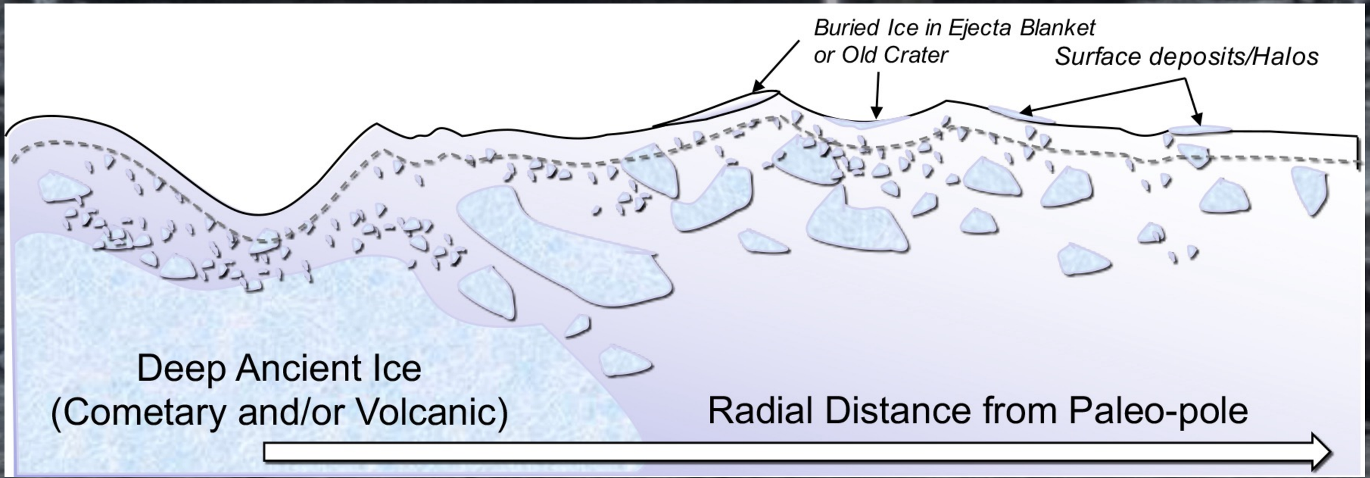


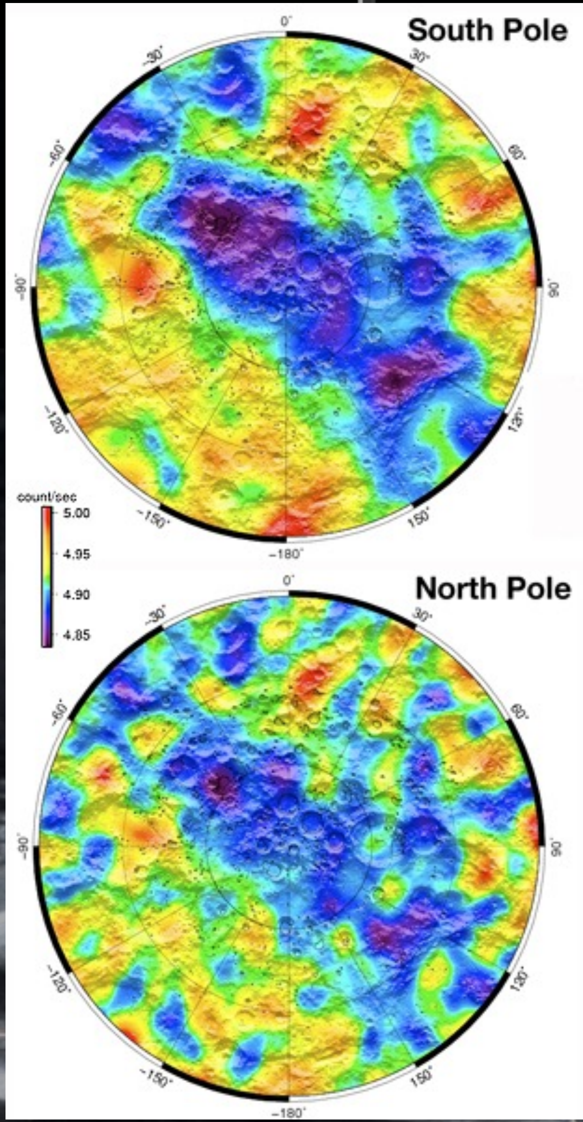


Polar Volatile Deposits

Commerce

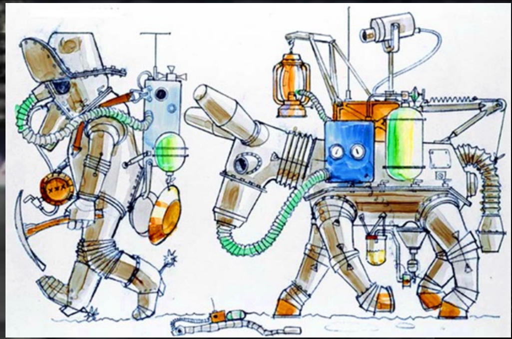
- Quantify the cost and potential profit of ISRU:
  - Composition – amount and type of impurities;
  - Grade of the prospect;
  - Extractability – geotechnical properties;
  - Refining, transport, and storage processes;
  - What the market is for such products.

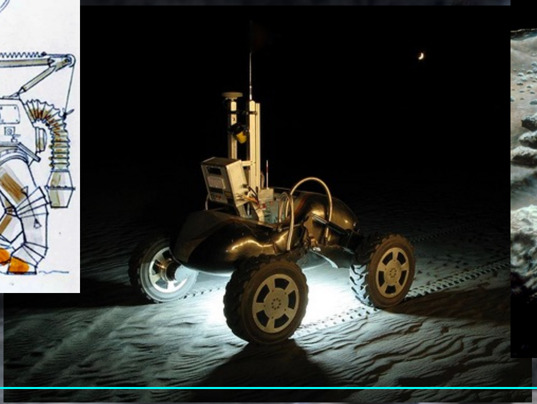




Lunar Polar Volatile Deposits: A Template for Other Resources

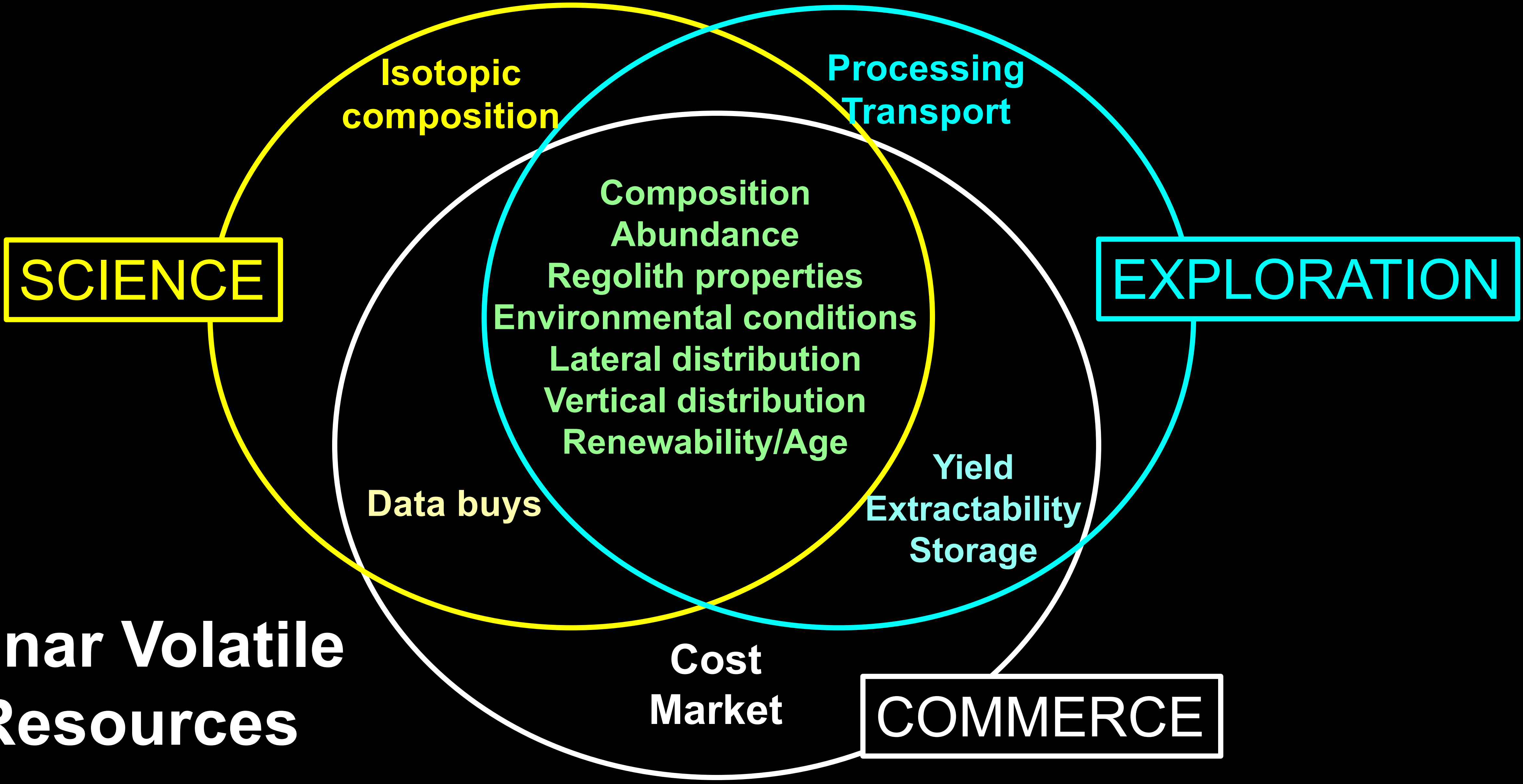
- Exploration and science synergies.
- Commercial interest in these resources that have science benefits.
- International interest in the polar volatiles – ~6 landed missions to the south pole over the next ~6 years (ISECG), with 3 from China and 2 from Russia.
- Initial in situ investigations that leads to cryogenic storage and sample return.
- Technology development in cryogenic sampling, transport, & curation, as well as cryogenic storage of refined products.
- Feed forward to other destinations (Mars, Comets, Ocean Worlds).





Prospecting campaign should involve science, exploration, and commerce as partners. No "science first" – essentially the same data inform all stakeholders

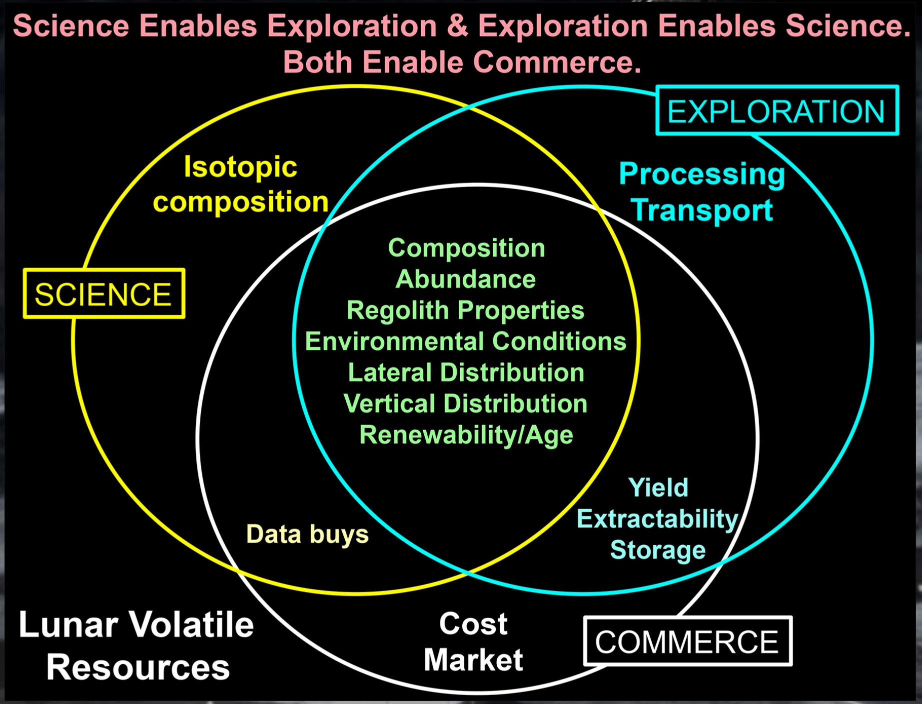
Science Enables Exploration & Exploration Enables Science.
Both Enable Commerce.



Lunar Volatile Resources

Lunar Resources

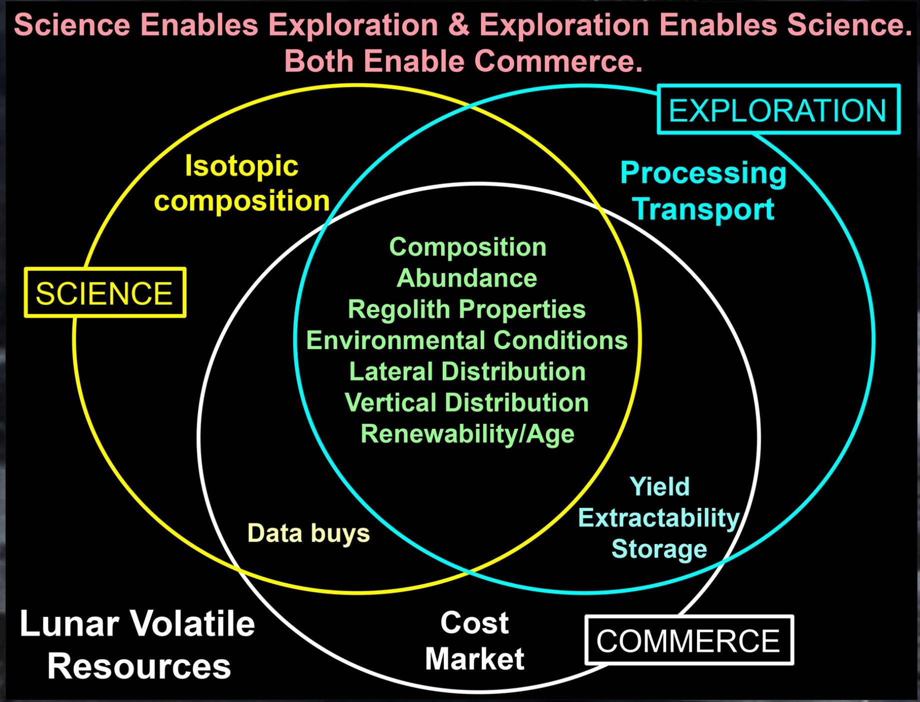
- Exploring lunar resources will yield data sets complementary to science, exploration, and commerce.
- Vital for sustainable human exploration of the Moon (living off the land – important feed-forward potential for Mars)
    - Sustainable: long-term, enduring (3 factors – financial, technical/risk, national policy*)
- Multi-decadal plan of Moon AND Mars (not Moon to Mars) that transcends politics.
- Development of a new sector of the economy (creates jobs!)
- Moon Technology thus developed should be transferrable to other destinations, including Earth.
- CLPS missions should be better utilized to develop such technology and prospecting strategies



* National Space Council (2020)A New Era for Deep Space Exploration & Development
https://aerospace.org/sites/default/files/2020-07/NSpC%20New%20Era%20for%20Space%2023Jul20.pdf

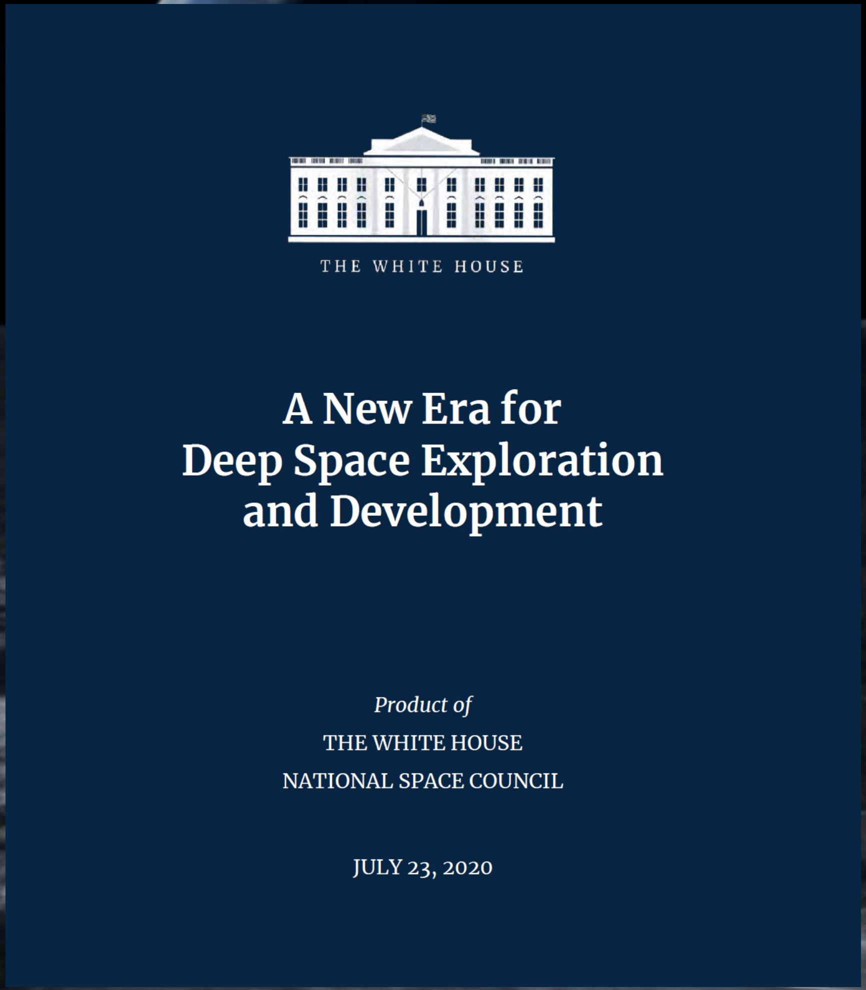
Lunar Resources

- The critical first step is to show the reserve potential of lunar resources.
- Requires a(n international) prospecting campaign with science, exploration, and commerce as equal partners – the data obtained obtained inform all.
- Full development of lunar resources facilitated by a permanent human presence.
- Requires Artemis Program Office to oversee integration of multiple stakeholders (SMD, HEOMD, STMD, lunar community, etc.):
  - Navigate the geo-political issues surrounding lunar exploration and use of resources;
  - Integrate science, exploration, and commerce within a(n international) prospecting campaign;
  - Expedite testing of critical technology and operations on the lunar surface.



Artemis should be inclusive: Moon AND Mars (& beyond)

Sustainability


THE WHITE HOUSE

A New Era for
Deep Space Exploration
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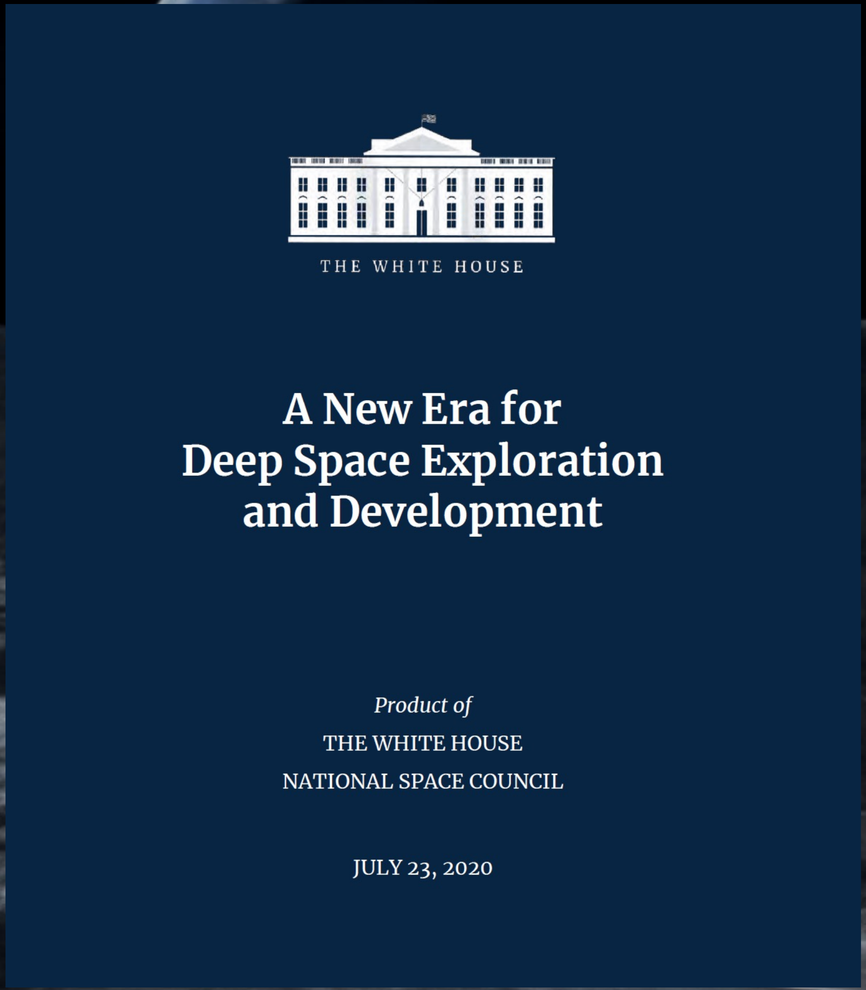
JULY 23, 2020

In order to be stable and sustainable over the long-term, America's space efforts must be strongly linked to, and supportive of, enduring national interests. From economic prosperity and national security to science and diplomacy, space activities provide practical as well as symbolic benefits to the nation.

https://aerospace.org/sites/default/files/2020-07/NSpC%20New%20Era%20for%20Space%2023Jul20.pdf

Sustainability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The term "sustainable" can have different meanings, depending on the context. For example, financial sustainability is the ability to execute a program of work within budget levels that are realistic, managed effectively, and likely to be available. Technical sustainability requires that operations are conducted repeatedly at acceptable levels of risk. Proper management of the inherent risks of deep space exploration and settlement is the key to making those risks "acceptable." Finally, policy sustainability means that the program's financial and technical factors are supportive of long-term national interests, broadly and consistently, over time.

Long-term deep space exploration and development should seek to have a similar level of policy sustainability. It can do so by ensuring such efforts promote and strengthen the technical, economic, and foreign policy objectives of the United States and its allies.